Environmental Influences in SGRs and AXPs

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Abstract.
Soft gamma–ray repeaters (SGRs) and anomalous x–ray pulsars (AXPs) are young ($<$100 kyr), radio-quiet, x-ray pulsars which have been rapidly spun-down to slow spin periods clustered at $5-12$ s. Nearly all of these unusual pulsars also appear to be associated with supernova shell remnants (SNRs) with typical ages $<$ 20 kyr. If the unusual properties of SGRs and AXPs were due to an innate feature, such as a superstrong magnetic field, then the pre-supernova environments of SGRs and AXPs should be typical of neutron star progenitors. This is *not* the case, however, as we demonstrate that the interstellar media which surrounded the SGR and AXP progenitors and their SNRs were unusually dense compared to the environments around most young radio pulsars and SNRs. Thus, if these SNR associations are real, the SGRs and AXPs can not be "magnetars", and we suggest instead that the environments surrounding SGRs and AXPs play a controlling role in their development.

I INTRODUCTION

Soft gamma–ray repeaters (SGRs) are neutron stars whose multiple bursts of gamma–rays distinguish them from other gamma–ray burst sources [1]. SGRs are also unusual x–ray pulsars in that they have spin periods clustered in the interval $5-8$ s, and they all appear to be associated with supernova remnants (SNRs), which limits their average age to approximately 20 kyr [2]. The angular offsets of the SGRs from the apparent centers of their associated supernova remnant shells indicates that SGRs are endowed with space velocities >500 km s^{-1}, which are greater than the space velocities of most radio pulsars [3]. Anomalous x–ray pulsars (AXPs) are similar to SGRs in that they are radio quiet x–ray pulsars with spin periods

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clustered in the range $6-12$ s, and have similar [4] persistent x–ray luminosities as the SGRs ($\sim 10^{35}$ ergs s^{-1}). Most of the AXPs appear to be associated with supernova remnants, and therefore they are also thought to be young neutron stars like the SGRs. Here we present a new look at environmental evidence which shows that the SGRs and AXPs can not be due to a purely innate property, such as superstrong magnetic fields [5].

II THE ENVIRONMENTS OF SGRS AND AXPS

If the unusual properties of SGRs and AXPs were due solely to an intrinsic property of the neutron star, that developed independently of the external environment, then the characteristics of the interstellar medium which surrounded the AXP and SGR progenitors should be typical of that around the massive O and B stars which are progenitors of all neutron stars. Observations clearly show that the majority of neutron stars are formed in "superbubbles": evacuated regions of the ISM which surround the OB associations in which the massive progenitors of most neutron stars live. The supernovae from the massive O and B stars which form SGRs and AXPs are heavily clustered in space and time and form vast (>100 pc) HII regions/superbubbles [6] filled with a hot ($>10^6$ K) and tenuous ($n\sim 10^{-3}$ cm^{-3}) gas. The occurrence of most supernovae in the hot phase of the ISM is confirmed from observations of nearby galaxies [7] and from studies of Galactic SNRs [8]. It is estimated that $90\pm 10\%$ of all core-collapse supernova should occur in this hot and tenuous environment [9].

The environments of SGRs and AXPs are probed by the blastwaves of their associated supernova remnants, and from the size of the remnant shell as a function of the age we can constrain the external density. In Table 1 we have listed the 12 known SGRs and AXPs and their associated supernova remnant shells [10]. The identification of the associated remnants are based on both positional coincidences of the remnant and the SGR/AXP, and on similar distances of the SGR/AXP and its associated remnant. We include the new tentative [11] SGR candidate 1801–23, which appears to be associated with the SNR W28. The thin SGR error box passes roughly through the center of the SNR and through the compact, nonthermal x–ray source [12] within the remnant. No associated remnants can be found for AXPs 0720–3125 and 0142+615, which is not surprising given the close distance (~ 0.1) of 0720–3125 [13], and the molecular clouds associated with 0142+615 [14]. A more detailed discussion and reference list for the sources in Table 1 will be published elsewhere [10].

Most of the SGR/AXP positions are significantly displaced from the apparent centers of their associated SNRs, as can be seen in Table 1 from the ratio of the neutron star angular displacement θ_* divided by the angular radius θ_{SNR} of the remnant shell. These displacements clearly indicate that the SGR/AXPs have large transverse velocities. There is considerable uncertainty in the actual velocities, however, because the estimated remnant ages are probably uncertain by a factor of

Table 1. The Supernova Remnants of SGRs and AXPs

Object	Period (s)	SNR	Age[a] (kyr)	Dist. (kpc)	Rad.[b] (pc)	$\frac{\theta_*}{\theta_{SNR}}$	Vel.[c] (km s^{-1})
SGR 1627–41	6.4?	G337.0−0.1	5	11	2	2.3	1000
AXP 1841–045	11.8	Kes 73	2	6.5	4	0.1	200
AXP 1845–0258	6.97	G29.6+0.1	10	12	8	0.1	200
SGR 0526–66	8	N49	5.5	55	8	0.8	1200
AXP 1709–40	11.0	G346.6–0.2[d]	20	10	12	1.7	1000
SGR 1900+14	5.16	G42.8+0.6	10	5	15	1.4	2000
AXP 2259+586	6.98	CTB 109	10	4	16	0.2	300
SGR 1806–20	7.47	G10.0–0.3	10	14.5	16	0.5	800
SGR 1801–23	–	W28[d]	60	3	19	0.1	30
AXP 1048–5937	6.45	G287.8–0.5[d]	10	3	11	2.2	1100
AXP 0720–3125	8.39	–[e]	50[f]	0.1	–	–	–
AXP 0142+615	8.69	–[g]	60[f]	1	–	–	–

[a]SNR age

[b]Radius of radio shell

[c]Transverse velocity of SGR/AXP

[d]"Tentative" remnant identification (see text)

[e]Too close to identify remnant

[f]MDR timing age since there is no SNR

[g]In/behind molecular cloud (no remnant)

two in most cases, which introduces a corresponding uncertainty in the transverse velocities. In addition, the actual space velocities of the SGR/AXPs are larger by an unknown factor dependent on the viewing angle. Nonetheless, the data suggest that the typical SGR/AXPs are of the order of 1000 km s^{-1}. Such velocities, while much larger than the typical neutron star velocities, are not unprecedented, as $\sim 10\%$ of radio pulsars may have space velocities of 1000 km s^{-1} or greater [3]. We conclude, therefore, that the SGRs and AXPs are a *high velocity* subset of young neutron stars.

In Figure 1 we have plotted the SNR shell radii as a function of the estimated age of each remnant. Overplotted in solid lines are simple approximations of the evolutionary tracks [15] of supernova remnant expansion in the wide range of the external ISM densities, and we see that these SNRs are all in the denser (> 0.1 cm^{-3}) phases of the ISM which slow their expanding shells to < 2000 km s^{-1} in < 10 kyr. Also overplotted are the tracks of neutron stars born at the origin of the supernova explosion with varying velocities, showing the times required for fast (e.g. > 500 km s^{-1}) neutron stars to catch up with the slowing supernova ejecta and swept-up matter.

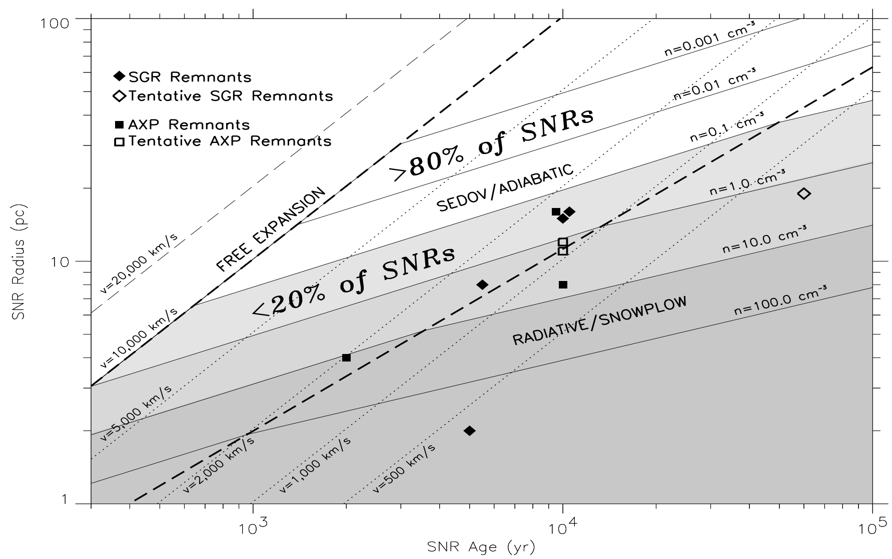

FIGURE 2. The radius of the SGR and AXP supernova remnant shells as a function of their age. The solid lines denote SNR expansion trajectories and the dotted lines denote the tracks of neutron stars born at the origin of the supernova explosion with varying space velocities. We see that essentially all of these sources were formed in the denser phase of the interstellar medium (ISM), which clearly indicates that the environment, and not a purely intrinsic property such as a superstrong magnetic field, is the controlling factor in the development of the SGRs and AXPs

III DISCUSSION

From the discussion in § II, we saw that neutron stars should preferentially reside in the diffuse ($n < 0.01$ cm^{-3}) gas which constitutes the hot phase of the interstellar medium. As seen from Figure 1, however, the SGRs and AXPs tend form in denser regions of the ISM. Given the entire sample of AXPs and SGRs, the probability that this is merely due to chance depends on the the ability to detect supernova remnants in the different phases of the interstellar medium. For the SGRs, the detection sensitivity is independent of the interstellar medium, because they are detected via their bright gamma–ray/x–ray bursts. Therefore, using only the SGRs yields a chance probability of less than $(0.2)^5 \sim 10^{-4}$, if one accepts the tentative W28/SGR 1801–23 association, and $\sim 10^{-3}$ if one excludes SGR 1801–23 from the SGR sample. The AXPs are also preferentially in the dense phase, which further lowers the chance probability for the class as a whole. The evidence then suggests that the environments surrounding SGRs and AXPs are significantly different than otherwise normal neutron stars in a way which is *inconsistent* with the hypothesis that the properties of these sources are the result of an innate characteristic such as a superstrong magnetic field.

These observational facts imply instead that the environment is crucial in the development of SGRs and AXPs. One plausible scenario is that the rapid spin-down of the SGR/AXPs may result from their interaction with co-moving ejecta and

swept-up ISM material [16] [17]. Calculations [10] indicate that such an *interaction* scenario, involving the formation of accretion disks by fast (> 500 km s^{-1}) neutron stars from co-moving ejecta of supernova remnants slowed to < 2000 km s^{-1} by the denser (> 0.1 cm^{-3}) phases of the ISM, could spin-down SGRs and AXPs to their present-day spin periods in ~ 10 kyr – consistent with the estimated ages of these sources – without requiring the existence of a population of neutron stars with ultrastrong magnetic fields. In addition, such a scenario can explain the clustering of spin periods, present-day spin-down rates, and the number of SGRs and AXPs in our galaxy [10].

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